Performance of a New Generation of Acoustic Current Meters

NELSON G. HOGG AND DANIEL E. FRYE

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

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ABSTRACT

As part of a program aimed at developing a long-duration, subsurface mooring, known as Ultramoor, several modern acoustic current meters were tested. The instruments with which the authors have the most experience are the Aanderaa RCM11 and the Nortek Aquadopp, which measure currents using the Doppler shift of backscattered acoustic signals, and the Falmouth Scientific ACM, which measures changes in travel time of acoustic signals between pairs of transducers. Some results from the Doppler-based Sontek Argonaut and the travel-time-based Nobska MAVS are also reported. This paper concentrates on the fidelity of the speed measurement but also presents some results related to the accuracy of the direction measurement. Two procedures were used to compare the instruments. In one, different instruments were placed close to one another on three different deep-ocean moorings. These tests showed that the RCM11 measures consistently lower speeds than either a vector averaging current meter or a vector measuring current meter, both more traditional instruments with mechanical velocity sensors. The Aquadopp in use at the time, but since updated to address accuracy problems in low scattering environments, was biased high. A second means of testing involved comparing the appropriate velocity component of each instrument with the rate of change of pressure when they were lowered from a ship. Results from this procedure revealed no depth dependence or measurable bias in the RCM11 data, but did show biases in both the Aquadopp and Argonaut Doppler-based instruments that resulted from low signal-to-noise ratios in the clear, low scattering conditions beneath the thermocline. Improvements in the design of the latest Aquadopp have reduced this bias to a level that is not significant.

1. Introduction

In the late 1960s engineers at the Woods Hole Oceanographic Institution developed the vector averaging current meter (VACM; McCullough 1975) and this instrument became the Institution's standard for making horizontal velocity measurements on subsurface moorings. Mooring technology was also under active development and by the 1970s had become increasingly reliable to the point where 2-yr measurements have become routine (Heinmiller and Walden 1973). Although data retrieval from these moorings often exceeds 90%, common failure points are the mechanical sensors (e.g., Savonius rotor, vane, compass, and vane follower) and the cassette-based data recorder. As physical oceanography has evolved in the past three decades to place more emphasis on long-time-scale problems associated with climate variations, the 2-yr limitation of the present mooring technology has become increasingly burdensome and expensive. Time series of at least decadal length are of interest and the need for frequent replacement and refurbishment of moorings has made the existing technology very expensive. Therefore, we initiated the development of a subsurface mooring system that would last up to 5 yr and periodically release capsules that telemeter data back to the laboratory (see Frye et al. 2004). As part of this development, we decided to investigate a new generation of low-power, acoustically based current meters because they have no mechanical subsystems, can function for 5 yr at reasonable sampling rates, and have the capability of electronically transferring data to acoustic modems. Naively expecting to make the choice of which instruments met our requirements based on price and advertised capabilities, we made a short list that placed emphasis on those with which we had some familiarity and fit within our budget (Table 1).

To narrow the field we initiated a modest at-sea testing program. All tests were performed at approximately the same location about 80 km southeast of Ber-

Corresponding author address: Dr. Nelson Hogg, Woods Hole Oceanographic Institution, MS 21, Woods Hole, MA 02543.
E-mail: nhogg@whoi.edu

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TABLE 1. Instruments used on the test moorings and lowerings. An empty box signifies that an instrument was not used, and the other notations indicate a generation or configuration.

Instrument	Type	Manufacturer	Ultramoor-1	Ultramoor-2	Minimoor	Lowering 1	Lowering 2	Lowering 3
VACM	Mechanical, Savonius rotor	EG&G	X	X				
VMCM	Mechanical, propeller	EG&G			X			
RCM11	Acoustic, Doppler	Aanderaa	X	X	X	X	X	
AQD (four generations)	Acoustic, Doppler	Nortek	1	2		2	3	4
ARG	Acoustic, Doppler	Sontek					X	
MAVS (second and third generations)	Acoustic, travel time	Nobska	2		3		3	
ACM (2D and 3D)	Acoustic, travel time	Falmouth Scientific	2D	3D	3D	3D	3D	

muda and took two forms: moored intercomparisons, which are described in section 2, and those done by shipboard lowerings as outlined in section 3. The instruments used in each of these situations are tabulated in Table 1. Conclusions are discussed in section 4.

Very close to this site, a similar intercomparison was done earlier by Gilboy et al. (2000) utilizing a surface mooring known as the Bermuda Testbed Mooring. In this study velocities near 72-m depth measured by a VMCM, an ACM, and an acoustic Doppler current profiler (ADCP) were compared and found to be in agreement within statistical error except for a 20°–30° direction discrepancy attributed to the ACM. The reader is also referred to the review of modern current measuring techniques given in Dickey et al. (1998) and to a comparison of the ADCP with a VACM and VMCM reported by Irish et al. (1995).

2. Moored tests

The Ultramoor development schedule provided two opportunities to compare instruments (see Table 2). Problems revealed by the first deployment and telemetered data from the second led to a third mooring called Minimoor because it rose just 300 m above the bottom, unlike the other two that came within 150 m of the surface. All moorings were deployed in about 4300 m of water close to the same location southeast of Bermuda using the R/V *Weatherbird*. They are discussed chronologically below.

a. Ultramoor-1

This was the first field test of the Ultramoor system and it lasted about 3.5 months from August to November of 2000. All of the current meters on the mooring were located near 2000-m depth with a spacing of about 10 m (Fig. 1, Table 2) and all returned some data, although not all lasted through the full deployment. The instruments available from this mooring for intercomparison are an ACM (see the Web site http://www.falmouth.com), an AQD1 (http://www.nortekas.com), a MAVS2 (http://www.nobska.net), and an RCM11 (http://www.aanderaa.com), all sandwiched by two VACMs. The AQD1 was the first delivered for deep-water work and the transmit pulse resonated with the pressure case (L. Gordon 2002, personal communication), rendering its velocity data unusable. The 2D-ACM was the only instrument to be interfaced with an acoustic modem and the handshaking with the modem caused the time base to be variable and the batteries to be consumed early. As a result, only comparisons between the VACMs (it makes little difference which one we use because the data are essentially identical) and the MAVS and RCM11 instruments are shown in Fig. 2. To make these comparisons, the east and north components of the more rapidly sampled instrument (in this case the VACM) were interpolated onto the time base of the other instrument yielding time series of synchronized velocity components. From these data, speed and direction differences between the test instrument and the reference (the bottom VACM) were calculated and scatterplots produced.

Considering the speed differences first, we see that there is little to distinguish the two VACMs: the straight-line fit has a slope very close to zero though there is substantial scatter in the data. On the other hand, it is clear that there are significant speed differences between the other two instruments and the reference VACM, with the RCM11 generally reading lower by an amount that increases with speed. This suggests a linear relationship, but with the RCM11 lower by about 25% (roughly 4 cm s^{-1} when the

TABLE 2. The six opportunities associated with the Ultramoor development program in which acoustically based instruments have been compared either with more traditional instruments based on mechanical speed and direction sensors or with the lowering rate of the instrument. Numerals after the MAVS and AQD signify the generation of the instrument. The ACM was manufactured as either a 2D (two horizontal axes) or 3D instrument as indicated. Here, "cont" indicates continuous and "inst" is instantaneous.

Expt	Type	Water depth (m)	Start date	End date	Instruments	Depth (m)	Duration (days)	Sampling rate (Hz)	Avg interval (min)	Sampling interval (min)
Ultramoor-1	Subsurface mooring tall	4552	30 Jul 2000	11 Nov 2000	VACM	1967	102	Cont	3.75	3.75
					2D-ACM	1974	57	2	Variable	Variable
					AQD1	1980	—	—	—	—
					MAVS2	1986	69	2	5	5
					RCM11	1993	102	0.5	5	5
					VACM	2000	102	Cont	3.75	3.75
Ultramoor-2	Subsurface mooring tall	4370	20 Nov 2001	5 Feb 2004	RCM11	2002	806	0.042	60	60
					VACM	2013	347	Cont	30	30
					AQD2	2025	806	23	2	60
					3D-ACM	4042	806	2	5	60
					RCM11	4055	806	0.042	60	60
Minimoor	Subsurface mooring short	4300	3 Apr 2002	29 May 2002	3D-ACM	3988	54	2	10	10
					RCM11	3991	56	0.5	5	5
					RCM11	3997	56	0.5	Burst	5
					VMCM	4000	56	Cont	3.75	3.75
					MAVS3	4003	56	2	0.33	0.33
Lowering 1	Lowering beneath CTD	~4300	24 Sep 2002	25 Sep 2002	3D-ACM	—	—	2	Inst	0.25
					RCM11	—	—	5	0.3	0.3
					AQD2	—	—	23	0.017	0.017
Lowering 2	Lowering from ship	~4300	20 Aug 2003	21 Aug 2003	3D-ACM	—	—	2	0.5 s	0.5 s
					RCM11	—	—	5	0.57	0.57
					AQD3	—	—	23	0.017	0.017
					ARG	—	—	1	0.167	0.167
Lowering 3	As above	~4300	15 Jun 2005	16 Jun 2005	AQD4	—	—	23	0.017	0.017

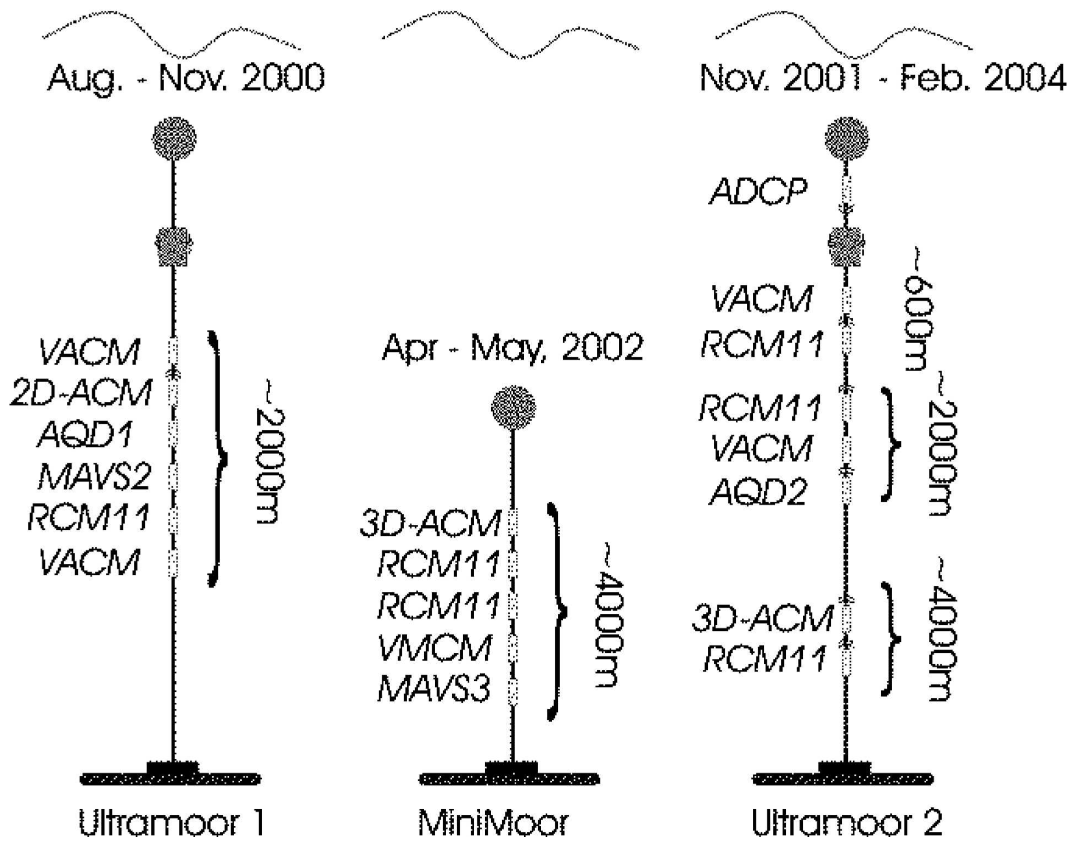

FIG. 1. The three moorings on which current meters were compared.

VACM reads 15 cm s^{-1}). The MAVS2 shows a relatively constant offset toward higher speeds than the VACM of about 2–3 cm s^{-1} with somewhat more scatter in the data.

The upper two scatterplots of speed in Fig. 2 give the impression that the noise in the VACM measurement is higher than that of the RCM11 as the scatter of the difference between the two VACM measurements is about twice that of the VACM − RCM11 difference. However, it must be remembered that the two VACMs are separated by 33 m whereas the RCM11 and the reference VACM are separated by just 7 m: if the RCM11 is referenced to the other VACM, the scatter increases to a level comparable to that of the difference between the two VACMs.

The direction differences (Fig. 2, right panels) show that the RCM11 compares very well to the VACM, at least as well as does the second VACM. The MAVS2, however, has much larger scatter and a bias that is a function of direction.

b. Ultramoor-2

This mooring was deployed in November 2001 and subsequently recovered in February 2004 after about 2.2 yr in the water. The mooring contained different groups of instruments at three depths for cross-referencing (Fig. 1, Table 2). Unfortunately, the shallow RCM11 near 600 m flooded and did not return useful data so its comparison with the collocated VACM could not be performed. Surrounding a VACM near 2000 m, the same intercomparison depth as in Ultramoor-1, there were two Doppler instruments, an RCM11, and an AQD2 whose transducer had been redesigned to prevent the ringing that occurred on Ultramoor-1. In addition, at 4000 m an RCM11 and a 3D-ACM were installed.

At the 2000-m level, the scatterplot for the RCM11 referenced to the VACM (Fig. 3, upper left) documents lower speeds for the RCM11 and the least squares fit is similar to that for Ultramoor-1 (Fig. 2, middle left). The AQD2 (Fig. 3, middle left) shows consistently higher speeds than the VACM across the range of speeds observed. This behavior was found to be the result of the low scattering levels at this depth and led to changes in the transducer and data processing algorithms (see section 3). At 4000-m depth there was no reference instrument and the RCM11 and 3D-ACM measured speeds that were consistently different, with the 3D-ACM re-

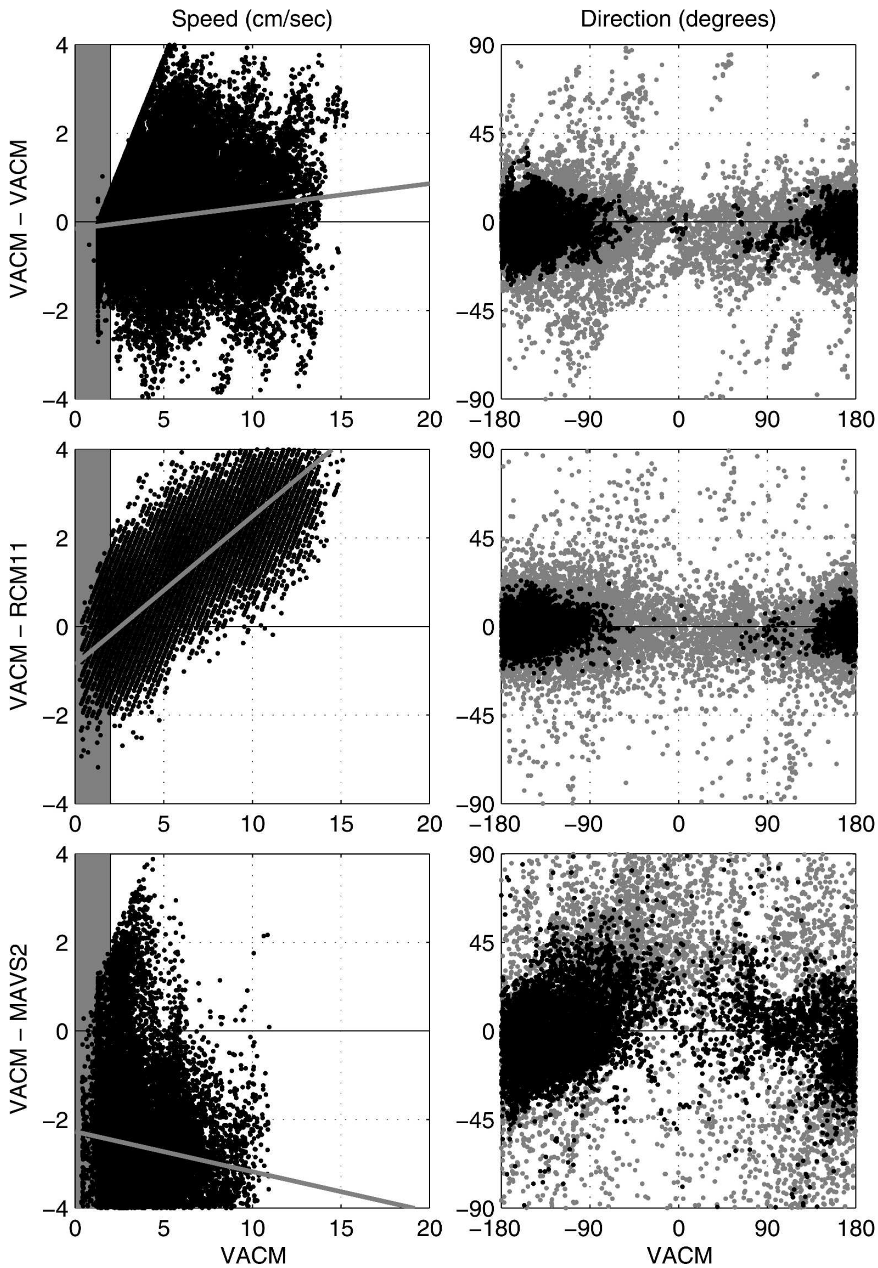

FIG. 2. Scatter diagrams for (left) speed difference and (right) direction difference between (top) the VACM, (middle) the RCM11, (bottom) the MAVS and the bottom VACM on Ultramoor-1. The data for the reference VACM, sampled at a 3.75-min interval, have been interpolated to the coarser sampling rates of the RCM11 and MAVS (5 min). The lines are least squares fits for VACM speed values greater than 2 cm s^{-1}. The darker points in the direction difference plots indicate when the speed is greater than 5 cm s^{-1} while the lighter ones are for speeds less than this value. Speed differences with magnitude greater than 4 cm s^{-1} are not displayed.

cording speeds more than 50% higher on average than the RCM11 throughout the measurement range. The overall energy levels recorded by the RCM11 were similar to those seen at 2000 m and by other instruments that have been moored in this area (see, e.g., McKee et al. 1981) so we suspect that the 3D-ACM is overestimating the current.

The right-hand panels in Fig. 3 show that the lowest scatter in direction and most consistent results across the range come from the RCM11, although there is an

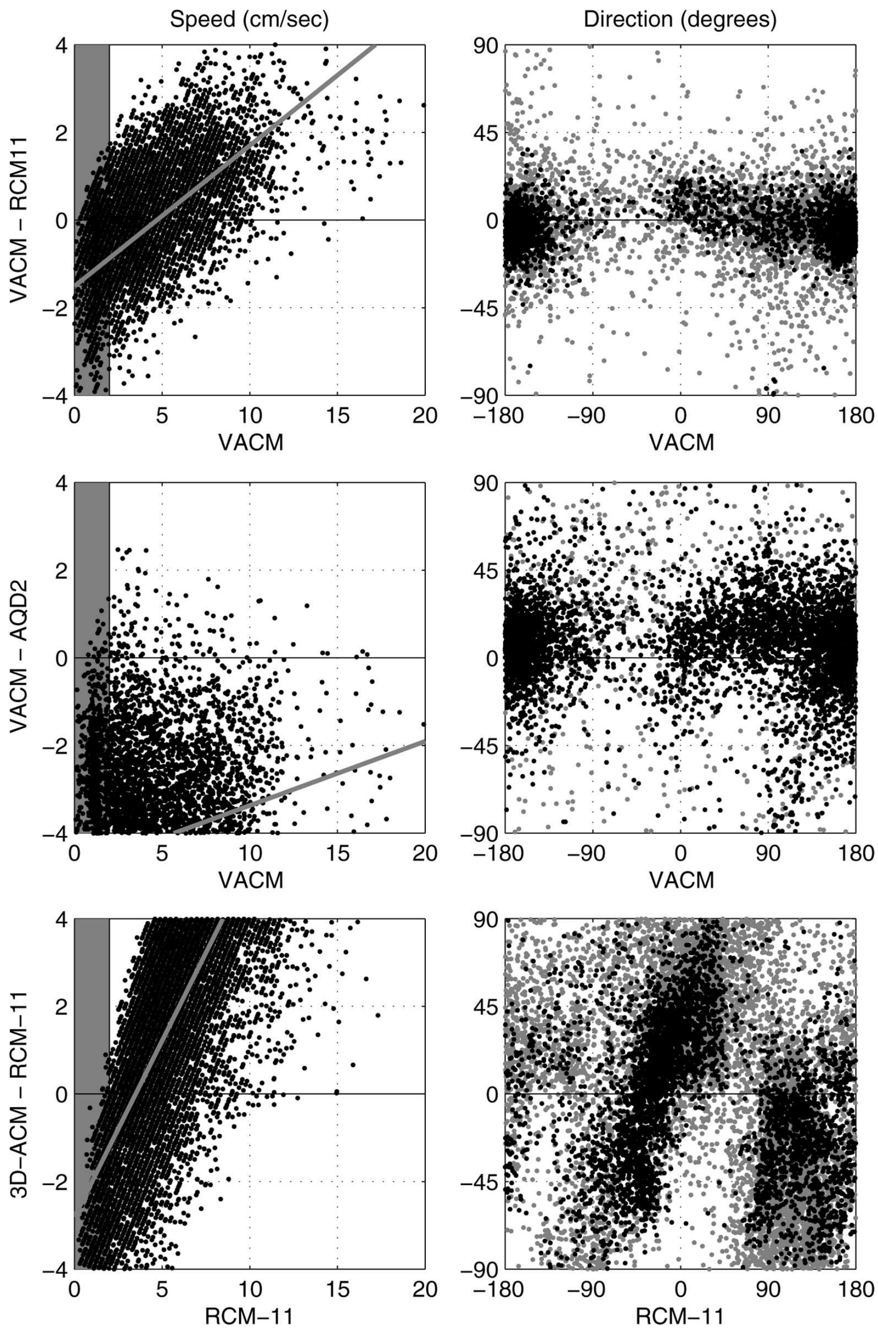

FIG. 3. As in Fig. 2 but for the second Ultramoor deployment. In this case the data for the VACM, averaged over 30-min intervals, have been interpolated to the coarser sampling rate of the RCM11 (60 min) and the 3D-ACM.

offset of about $-10°$ relative to the VACM. Although the AQD2 suffered from bias in its transducers, this did not greatly affect the computed directions, suggesting that the bias is the same for each transducer. The greater scatter most likely results from the fact that the AQD2, although sampling at 23 Hz, can only keep up this rate for 2 min out of each hour that a value is recorded, unlike the RCM11 that collects 150 equally spaced samples over the hour and thereby does a better job of filtering out high frequencies. It appears that the compass in the 3D-ACM (Fig. 3, lower right) is not performing properly, assuming that the RCM11 at 4000 m performed as well as the instrument at 2000 m.

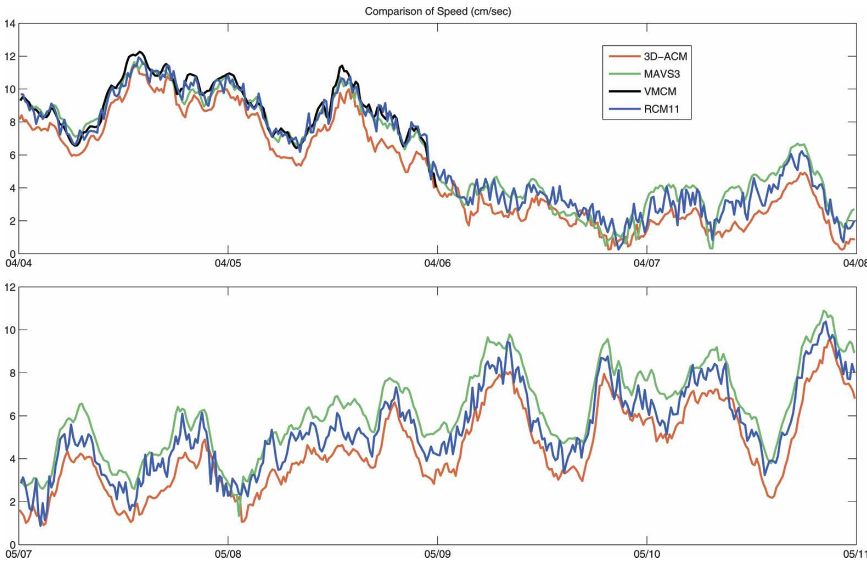

FIG. 4. Two 4-day periods from Minimoor showing the speeds measured by the MAVS3, the RCM11, the VMCM, and the 3D-ACM. No VMCM data are shown after the second day when one of its rotors failed. The RCM11 speeds have been increased by the factor 9/8 to compensate for the bias determined from the two Ultramoor moorings.

c. Minimoor

Because of the indication of biases revealed both by the data from Ultramoor-1 and that being telemetered from Ultramoor-2 (here the comparisons were between the RCM11, the AQD2, and the 3D-ACM as the VACM data were not telemetered), a short mooring, named Minimoor, was set close to Ultramoor-2 in spring 2002 for about 2 months. Five instruments were placed near 4000-m depth in water of about 4300 m (see Table 2). Some concern that the VACM was not performing adequately in the weak flows led us to use a vector measuring current meter (VMCM; Weller and Davis 1980) as the reference instrument. Unfortunately, one of the rotors on the VMCM stopped turning after 2 days, reducing the usefulness of this instrument for this purpose. However, with the experience accumulated from the two Ultramoor deployments, we decided to construct scatterplots from both the 2-day period when the VMCM was functional and, additionally, for the full 2 months, by using one of the two RCM11s as a reference with its speed adjusted to take into account the observed difference with the VMCM. We chose a factor of 9/8 from inspection of the VMCM − RCM11 differences, a factor that is somewhat lower than that indicated by either of the Ultramoor deployments (see next subsection).

Two 4-day snapshots of the speed measured by the four different comparison instruments are given in Fig. 4 with the top panel displaying data from the beginning of the deployment and the RCM11 adjusted by the 9/8 factor. For the first 2 days or so, the MAVS3, the RCM11, and the VMCM closely track each other as does the 3D-ACM but at 1 cm s^{-1} or so lower. Later in the deployment (Fig. 4, bottom) the MAVS3 is consistently higher than the adjusted RCM11 while the 3D-ACM continues to measure lower speeds.

The short-duration comparisons of the VMCM with the adjusted RCM11 speed and direction (Fig. 5, top panels) are now very similar. The 2-day comparison of the VMCM with the MAVS3 has a slight trend: speed differences increase with speed such that the MAVS3 observes higher speeds by about 1 cm s^{-1} than the VMCM at low speeds but this difference vanishes around 10 cm s^{-1} (black dots and line; Fig. 5, middle left). A similar trend is found when comparison is made for the full 2 months with the adjusted RCM11. Subsequent to the deployment, an electronic design problem was discovered in the MAVS3 that contributed a positive bias of about 1.5 cm s^{-1} at 25 cm s^{-1} (A. J. Williams III 2002, personal communication). The direction differences with respect to the VMCM indicate a nonlinear bias, although the number of data points from the first 2 days (black dots) is not very large. The direction comparison between the MAVS and the RCM11 over the full 2 months show little bias. The 3D-ACM speed comparison is reasonably good although the comparison with both the RCM11 and VMCM suggest that the 3D-ACM is biased low by close to 1 cm s^{-1} (see also Fig. 4). The directions of the 3D-ACM are offset from those observed by the VMCM and the RCM11 by about 10°.

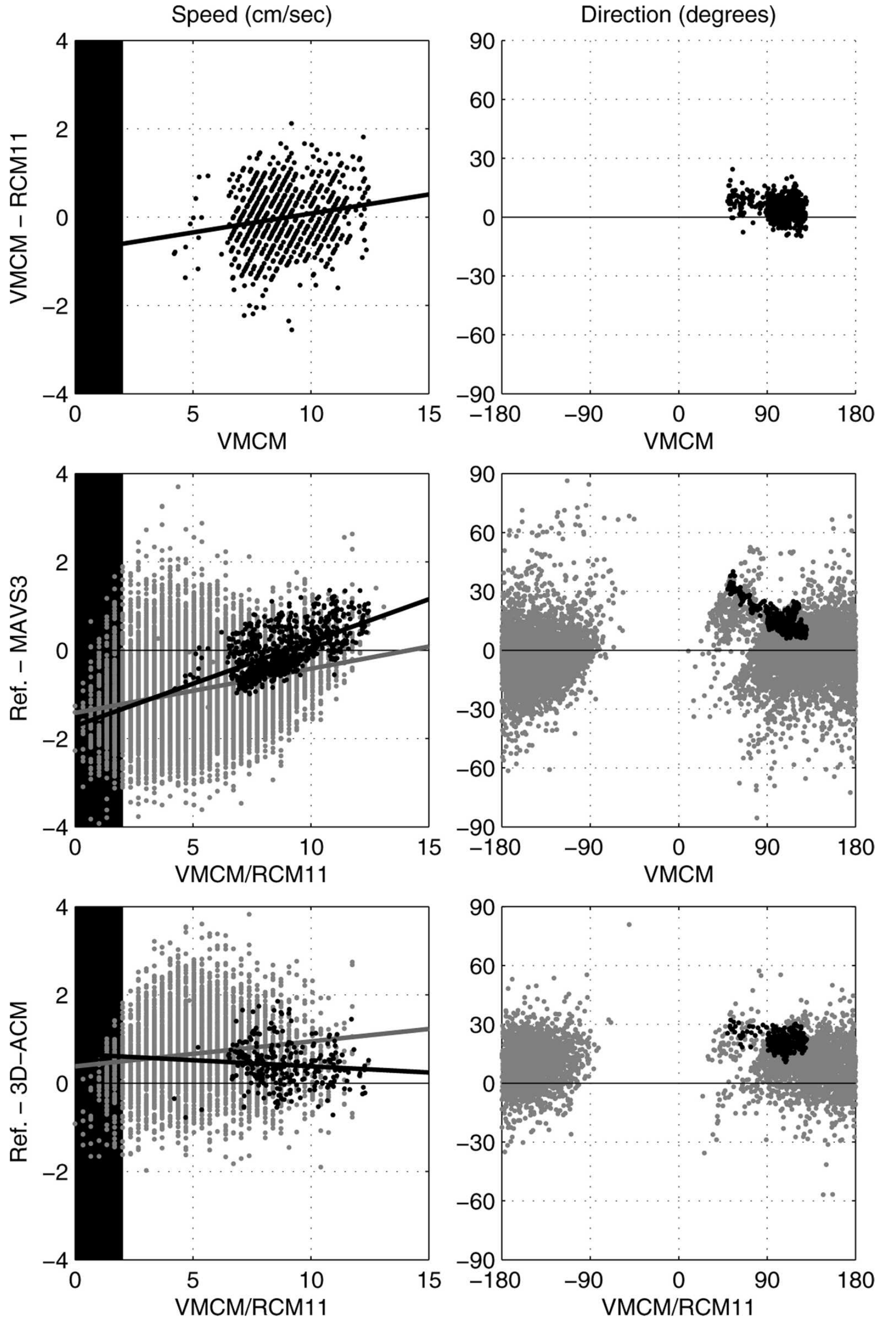

FIG. 5. As in Fig. 2, but for the Minimoor deployment, which contained a VMCM rather than a VACM. Because the VMCM failed after 2 days, we have used two means of comparison: the dark black points and lines are derived from differences with the VMCM for the first 2 days and, for the lighter gray points and lines, the RCM11. All RCM11 speeds have been adjusted by the factor 9/8.

d. Mooring results summary

Using the VACM or the VMCM as the standard for comparison, the results presented above suggest the following with respect to the other instruments.

- RCM11: This instrument was the most reliable in terms of general data collection and had the most consistent performance. Figure 6 shows the behavior of the RCM11 in comparison with the VACM and VMCM from the three moored tests. With respect to

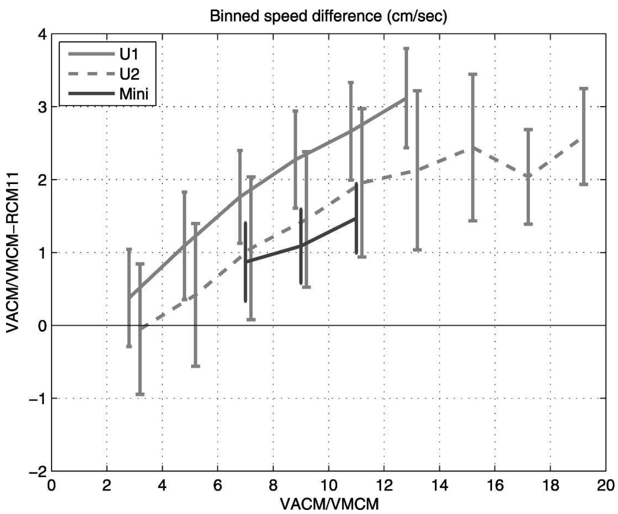

FIG. 6. Binned differences between speeds measured by either a VACM or a VMCM and an RCM-11.

both the VACM and VMCM the RCM11 measures lower speeds by 10%–25%, depending on mooring deployment, with indications that this difference levels off to a more uniform 2 cm s^{-1} above about 15 cm s^{-1}. It must be remembered that our testing locale near Bermuda is a very low speed regime with low scattering levels, a challenging environment for both mechanical and acoustic Doppler instruments.

- AQD: Two generations of this instrument have been used on the moorings. The first did not return useful data. The second, used on Ultramoor-2, did but the data are significantly biased, apparently by noise in the electronics circuits and signal processing issues.
- ACM: Two versions of this instrument were evaluated, each of which had the same transducer configuration, but the Ultramoor-1 version was configured to return only two-dimensional velocity information. Both Ultramoor deployments suffered from performance issues. Although considerable effort was taken to calibrate the instrument that was used on Ultramoor-2, its speeds were about 50% high relative to the RCM11 and directions were unreliable (Fig. 3, bottom). Contrasting with this experience, the 3D-ACM on Minimoor performed very well in measuring speed although a small bias was found for direction.
- MAVS: The MAVS2 used on Ultramoor-1 ran out of energy ⅔ of the way through the 3-month deployment and returned speeds consistently higher than the VACM by 1–2 cm s^{-1} (Fig. 2, bottom). Performance of the MAVS3 on Minimoor was improved but had an offset in the speed measurement amounting to 1.5 cm s^{-1} at 25 cm s^{-1}, traceable to an electronics issue. Direction differences with respect to the reference instruments indicate large offsets of a nonlinear character for the MAVS2 instrument on Ultramoor-1 but very good performance by the MAVS3 on Minimoor.

3. Shipboard lowerings

When the telemetered data from Ultramoor-2 began arriving, it was clear that there were discrepancies in the velocities coming from the two RCM11s and the AQD2 and 3D-ACM instruments with which they were collocated. In both cases the RCM11 measured substantially lower speeds than the other instruments, similar to the experience on Ultramoor-1 where the reference instrument was a VACM. The Minimoor was one attempt to resolve the issue.

A weakness of these moored comparisons is that they rely on a decision as to which instrument is considered the "standard." Certainly our bias is toward the venerable VACM and VMCM because we have had a great deal of experience with them over the past three decades, and because considerable effort has been made to calibrate their sensors in controlled situations (i.e., tow tanks). On the other hand, the new acoustic instruments rely on simple physical principles with which it is difficult to argue. However, their implementation depends on signal processing methods and sophisticated electronics that can introduce bias (L. Gordon 2002, personal communication). In addition, it is very difficult to find a tow tank large enough to perform controlled calibrations of the Doppler-based instruments because of the large volume that is insonified and the resulting problem of acoustic reflections from the walls of the tank.

Therefore, it was decided to attempt to calibrate the acoustic instruments by lowering them at a controlled and easily measured rate from a ship in roughly the same waters in which the moorings were located. This was not as easy as it might sound because neither the ship from which they were lowered nor the ocean were at rest, and these relative motions combined with the different sampling rates of the instruments complicate the results. For example, in Fig. 7 the vertical velocity of an AQD3 being lowered from the ship is shown for a 100-m segment of the water column. Two methods of measuring vertical velocity are illustrated: one computed from the rate of change of pressure and the other from the Doppler information received by the instrument. They agree well at the 1-Hz sampling rate and show an average descent of about 1 m s^{-1}. An oscillation of order 0.5 m s^{-1} amplitude with a period of around 6 s from swell-induced ship motion is superimposed. As we will see below, the different sampling strategies of the test instruments have differing degrees of success in filtering out this motion.

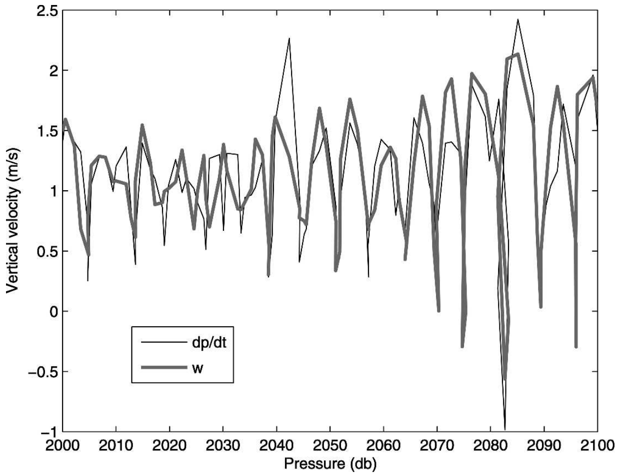

FIG. 7. Vertical velocity computed from the rate of change of pressure and from the Doppler shift of acoustic signals as measured by a third-generation AQD.

a. Lowering 1

This lowering took place in late September 2002. Three test instruments were suspended, with about 10-m separation, well beneath a CTD and kept vertical by hanging 200 lb of lead 10 m below the bottom instrument. The order of the instruments, from the bottom up, was an AQD2, then an RCM11, and finally a 3D-ACM. Both the AQD2 and the RCM11 were mounted horizontally with transducers aimed downward. In its normal vertical orientation this AQD2 was configured to have two orthogonal transducers in the horizontal plane and one midway between them at 45° to this plane. For the RCM11 to function in this orientation, it was necessary to manually freeze the output from the compass and tilt sensors. Sampling rates and averaging intervals are given in Table 2. Through an oversight, the 3D-ACM was not averaged over its sampling interval but was set to return instantaneous values every 15 s. At this low sampling rate the substantial ship motion was inadequately sampled and thus aliased into the results.

As it turned out, the CTD was superfluous to this test as the pressure sensor on the AQD2 was adequate for determining the lowering rate. The downward portion of the first cast is representative of the results (Fig. 8). To reduce the large swell-induced noise in the lowering rate, the different data streams were low-pass filtered to remove energy in periods shorter than about 2.5 min (or about 150 m at the 1 m s^{-1} lowering rate). The scattering levels upon which the two Doppler instruments depend vary considerably from the surface to the bottom, and reached a minimum a few hundred meters above the bottom (Fig. 8, right). With its rapid sampling rate and short sampling interval, the filtered data from the AQD2 (green line) are the least variable and there is good correspondence between the computed lowering rate (black line) and the vertical velocity computed from the Doppler data in the upper water column where signal strength is above about 35 counts. At lower signal strengths, found below about 1500 m, the two curves gradually diverge and indicate a bias of order +0.1 m s^{-1} at the lowest signal strengths.

The curves for the other two instruments are considerably noisier. For the 3D-ACM (Fig. 8, red line) this is not surprising given the inadequate sampling scheme, but the RCM11 deserves a little more comment. In "continuous mode" this instrument samples each transducer at 5 Hz, less rapidly than the 23 Hz used by the AQD2. The equally spaced pings are then simply averaged over the sample interval of 18 s. With the large vertical oscillations produced by the ship's roll happening at a 6-s period, shorter-time-scale energy leaks through the sidelobes of this crude low-pass filter and contributes to the higher variability.

A possible cause of the bias low and two periods of very low speeds near 700 and 3400 dbar was pointed out by the RCM11's manufacturer: the AQD2 and RCM11 instruments operate at very nearly the same frequency and there could have been some acoustic interference between the two. In addition, the RCM11 transducer was pointed directly down at the AQD2 leading to the possibility of the low speeds being a result of the wake above it. With these potential complications we undertook a second lowering cruise.

b. Lowering 2

By the time this second lowering took place, almost a year later in August 2003, we were able to use an AQD with transducers equally spaced by 120° and pointing up from the horizontal plane at 25°, allowing it to be lowered in the more conventional upright configuration and still measure the vertical component of velocity. The test RCM11 was again mounted horizontally but this time at the bottom of the instrument string and within a streamlined and weighted pod such that its transducers, and the associated measurement volumes, were well clear of the pod itself. Above these two a 3D-ACM was included, also in a horizontal position, but with a fin at its rear to orient it into the flow so that the transducer sting would be "upstream" of the lowering cable. In addition, there were as many as two Sontek Argonauts (ARG) included. A decreased lowering rate of about 0.3 m s^{-1} was used.

The results are shown in Fig. 9 and a similar pattern to the first lowering emerges. The AQD3 has a bias that grows with depth (and decreasing signal strength) to

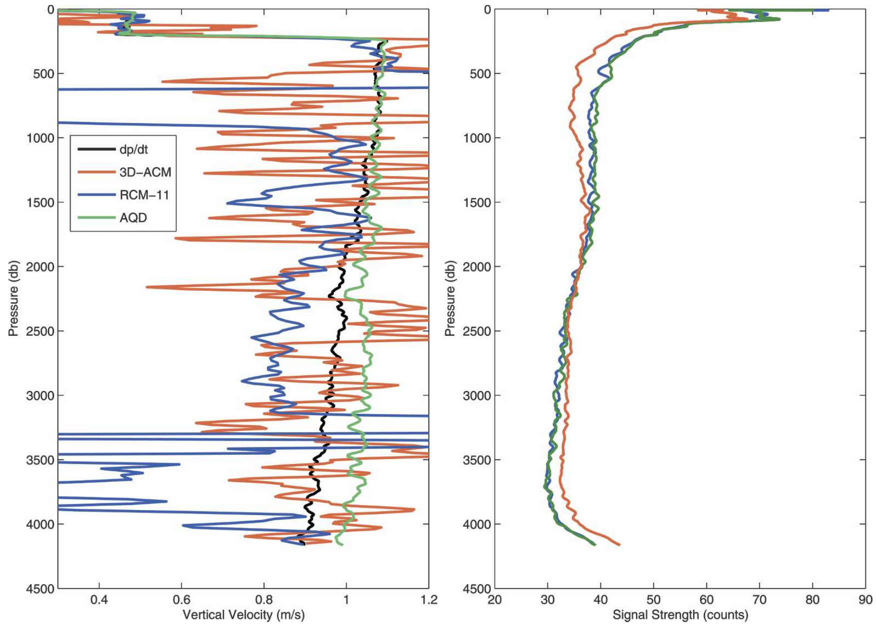

FIG. 8. (left) A comparison of vertical velocities measured by three different instruments with that computed from the rate of change of depth on the first lowering test. The velocities from the instruments have been adjusted for sound speed variations. (right) The Aquadopp signal strength for the three beams is shown as a function of depth. The signal strength scale is arbitrary. The black curve labeled "dp/dt" is computed from the rate of change of pressure in which pressure has been converted to depth.

reach about 0.1 m s^{-1}. This was the only opportunity we had to test the ARG and the associated results that we display came from one equipped with transducers of 2 times the diameter (40 mm) than previously had been used to increase its signal-to-noise ratio. Otherwise the ARG transducer configuration is similar to the AQD3 but with a slant of 45° from the horizontal instead of 25°. Its performance is similar to the AQD3 with a bias

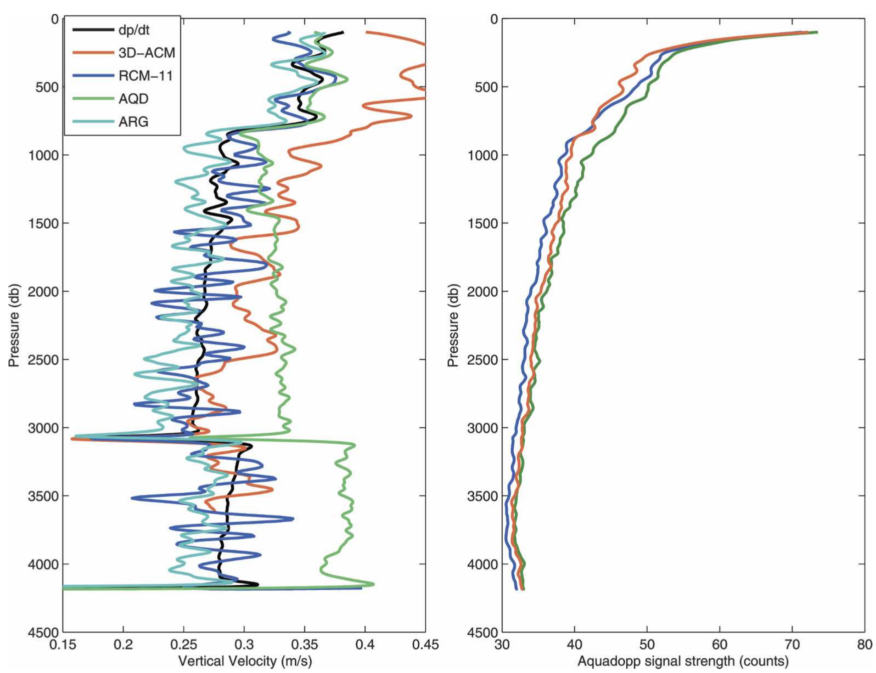

FIG. 9. As in Fig. 8 but for the second lowering test cruise.

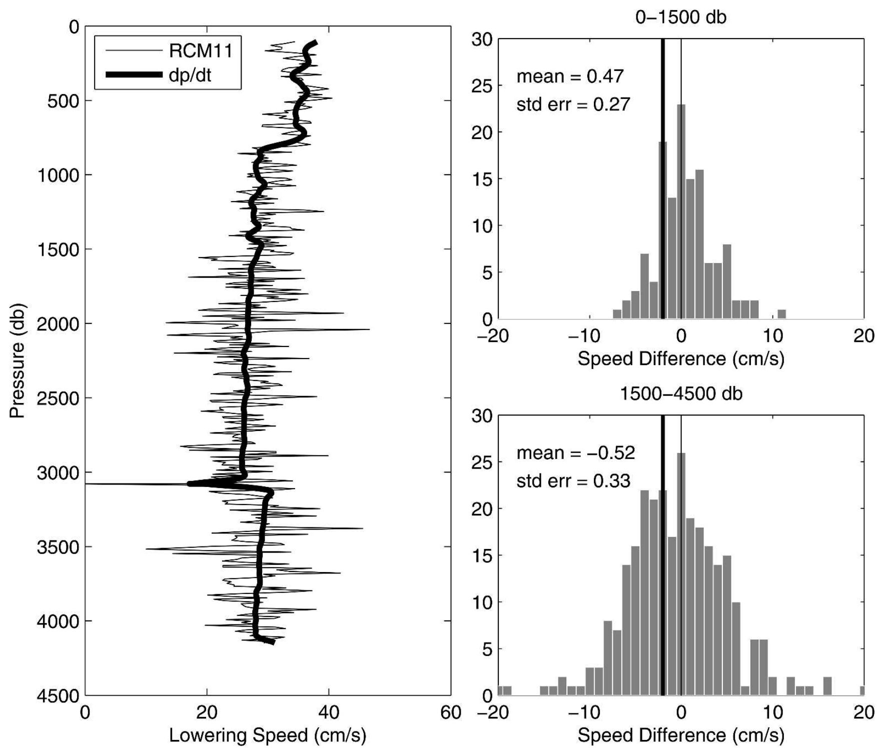

FIG. 10. A comparison of the RCM11 vertical velocity with actual lowering speed for the second lowering test. (left) The vertical component of the RCM11 velocity (thin noisy curve) and the low-passed lowering speed (heavy smooth curve). (right) Histograms of the difference between the RCM11 vertical velocity and that calculated in two pressure intervals. The heavy vertical line is at -2 cm s^{-1}; the fine one is at the origin.

that grows with depth and diminishing scatterers, although the ARG bias is smaller than that of the AQD3. The larger slant angle of the ARG transducers explains some, but not all, of this difference. The 3D-ACM results are the most puzzling. While it appears that this travel-time instrument measured the vertical velocity accurately between about 2500 and 3500 m, it shows considerable positive bias at shallower depths. One explanation is that the vane intended to keep the instrument pointed into the flow did not do its job very well and that allowed horizontal motion to contaminate the inferred vertical motion. The RCM11 data were greatly improved over the first lowering and the measured current profile has no visually discernable bias, although it would be difficult to detect visually the 2 cm s^{-1} suggested by the moored comparisons in the previous section.

To explore the RCM11 bias issue more quantitatively, histograms of the difference between the RCM11 vertical velocity component and the calculated lowering speed were calculated (Fig. 10). Because the actual orientation of the RCM11 in its pod was unknown, although fixed, the vertical component was determined by low-pass filtering the computed direction and then projecting the velocity into this direction, a more accurate calculation of the vertical component than total speed as is used in Figs. 8 and 9. This is overlaid with that computed from the AQD pressure record in the left panel in Fig. 10. In the right panels histograms of the difference between these two are shown, the top panel for the upper 1500 dbar and the bottom one for the rest. In both cases there is a peak in the histogram close to zero and the mean of all the differences is indistinguishable from zero. However, in both cases there is also a secondary peak near -2 cm s^{-1}, the value suggested by Fig. 6

c. Lowering 3

Prompted by results showing a bias in the AQD3 at low scattering levels, Nortek made two changes in the instrument (A. Lohmann 2005, personal communication). The biggest improvement came from changing the backing material for the transducers but some enhancement in performance was also achieved by modifications to the signal processing algorithm. Subse-

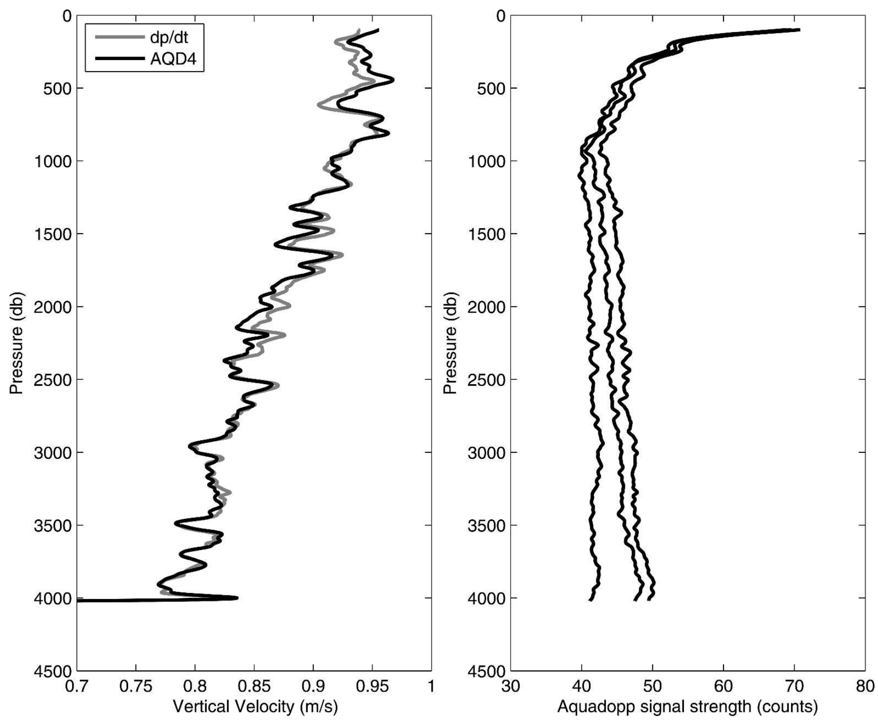

FIG. 11. As in Fig. 8 but for the third lowering. Here just one instrument, a fourth-generation Aquadopp, was tested.

quently, a final lowering test was performed in May 2005, once again south of Bermuda off the R/V *Weatherbird*. The comparison of the calculated rate of descent with the vertical velocity measured by the AQD4 is given in Fig. 11: with this fourth generation of the instrument the bias has become insignificant. A more quantitative display of the performance gains between the different AQD generations is provided in Fig. 12. There is some improvement between the second and third generations of the instrument but more dramatic improvement with the fourth whose bias is consistently 0.5 cm s^{-1} or less.

4. Conclusions

The RCM11 appears to have a small but systematic bias with respect to either the VACM or VMCM at low flow speeds, amounting to a 10%–25% reduction in measured speed up to 15 cm s^{-1}. Although we cannot be certain which instrument is biased, the fact that this shows up in comparisons with two reference instruments (i.e., the VACM and VMCM), both of which have had extensive tow tank calibrations, suggests that it may be a problem with the RCM11. At the Bermuda site, where the moorings were located, speeds rarely exceeded 20 cm s^{-1} but the results suggest that the bias levels are off by about 2 cm s^{-1} at speeds above 15 cm s^{-1}. This bias was consistent with bimodal histograms of differences between vertical velocity and lowering rate calculated using results from the second lowering experiment. Although the primary mode is near zero, a second mode close to -2 cm s^{-1}, with the

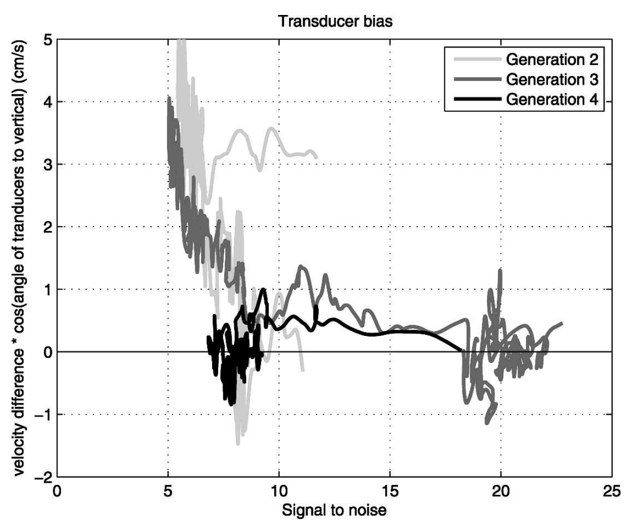

FIG. 12. Transducer bias vs signal-to-noise ratio for three generations of the AQD. The bias is calculated as the difference between the measured vertical velocity and the lowering rate projected into the relevant beam coordinate. The signal-to-noise ratio is calculated as 0.4 × (signal strength minus signal strength measured just after instrument recovery) according to the manufacturer's instructions (A. Lohmann 2005, personal communication).

RCM11 being low, is apparent. Directions measured by the RCM11 were consistently high quality as was the general performance of the instrument.

In our initial tests both the ARG and AQD revealed biases that were a function signal-to-noise ratio. In the deep subthermocline waters near Bermuda the water is sufficiently low in scatterers that the signal-to-noise ratio drops and a bias of as much as 5 cm s^{-1} along the transducer beam develops, which projects into 10 cm s^{-1} in the vertical velocity component. For the latest version of the AQD, Nortek has increased the efficiency of the transducers and improved the detection algorithm in the firmware to the point where a significant bias has been eliminated.

Our experience with both travel-time instruments—the ACM and the MAVS—is more limited. Direction and speed issues plagued the ACM, while endurance and minor technical issues hampered our testing of the MAVS. The Minimoor comparisons, however, suggest that, when operating properly, both are capable of making measurements within 1–2 cm s^{-1} of the reference instruments.

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REFERENCES

Dickey, T. D., A. J. Plueddemann, and R. A. Weller, 1998, Current and water property measurements in the coastal ocean. *The Sea—Ideas and Observations on Progress in the Study of the Seas,* K. H. Brink and A. R. Robinson, Eds., Vol. 10, The Global Coastal Ocean, John Wiley and Sons, 367–398.

Frye, D., N. Hogg, and C. Wunsch, 2004: A long duration mooring for ocean observation. *Sea Technol.,* **45,** 29–39.

Gilboy, T. P., T. D. Dickey, D. E. Sigurdson, X. Yu, and D. Manov, 2000: An intercomparison of current measurements using a vector measuring current meter, an acoustic Doppler current profiler, and a recently developed acoustic current meter. *J. Atmos Oceanic Technol.,* **17,** 561–574.

Heinmiller, R. H., and R. G. Walden, 1973: Details of Woods Hole moorings. Tech. Rep. WHOI-73–71, Woods Hole Oceanographic Institution, 23 pp.

Irish, J. D., A. J. Plueddemann, and S. J. Lentz, 1995: In-situ comparisons of moored acoustic Doppler profilers with conventional VACM and VMCM current meters. *Proc. IEEE Fifth Working Conf. on Current Measurements,* IEEE, St. Petersberg, FL, 59–64.

McCullough, J. R., 1975: Vector averaging current meter speed and calibration technique. Tech. Rep. WHOI-75-44, Woods Hole Oceanographic Institution, 41 pp.

McKee, T. K., E. A. Francis, and N. G. Hogg, 1981: Compilation of moored current-meter data from three topographic experiments: The Bermuda microstructure array, the island trapped waves array and the Gibbs Fracture Zone array. Tech. Rep. WHOI-81-68, Woods Hole Oceanographic Institution, 41 pp.

Weller, R. A., and R. E. Davis, 1980: A vector measuring current meter. *Deep-Sea Res.,* **27,** 565–581.